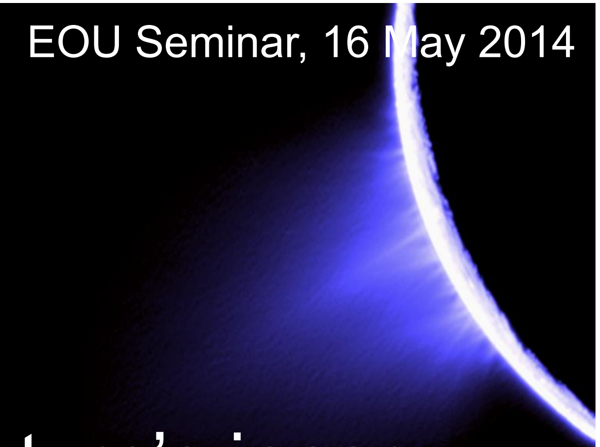
EOU Seminar, 16 May 2014



# Dust-plasma interaction in Saturn’s inner magnetosphere and its magnetosphere-ionosphere coupling

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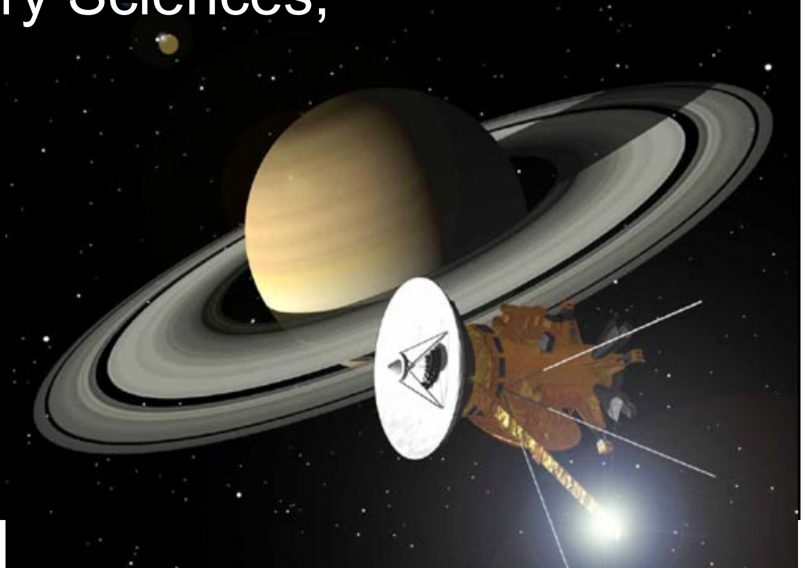


# Outline

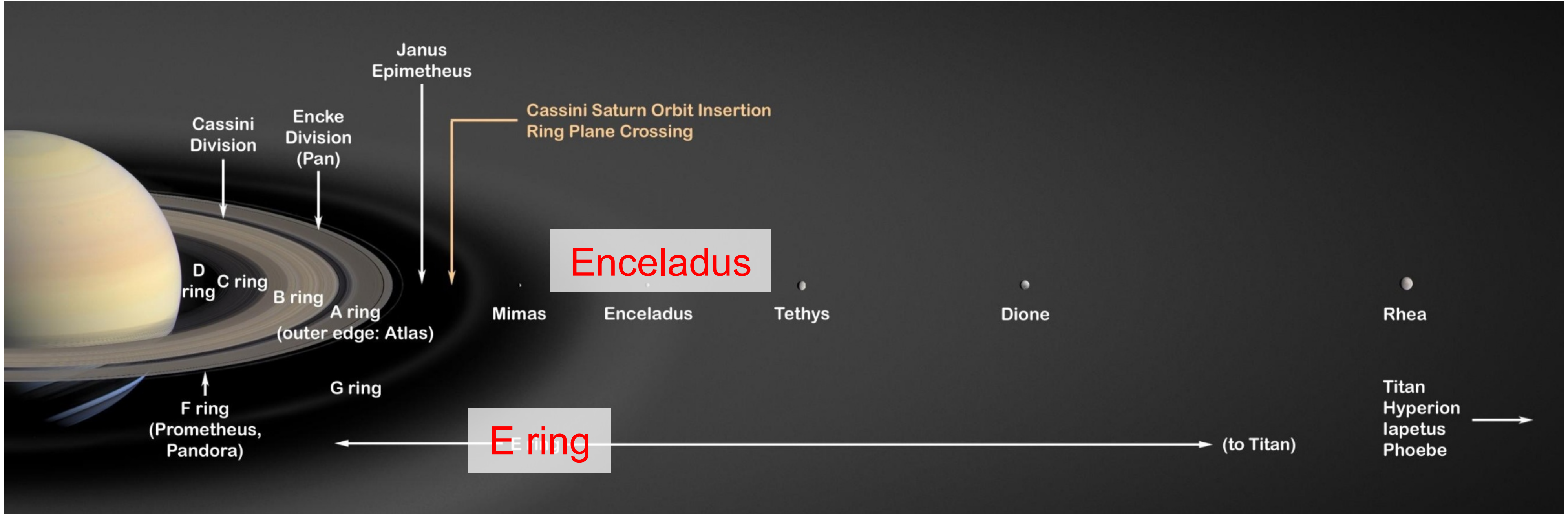
1. Introduction
    1. Saturn’s system
    2. Plasma and dust in Saturn’s inner magnetosphere
    3. Modeling of the inner magnetosphere
2. Modeling of the ionosphere
3. Magnetosphere-ionosphere coupling
4. Summary

# Introduction

# Saturn’s system

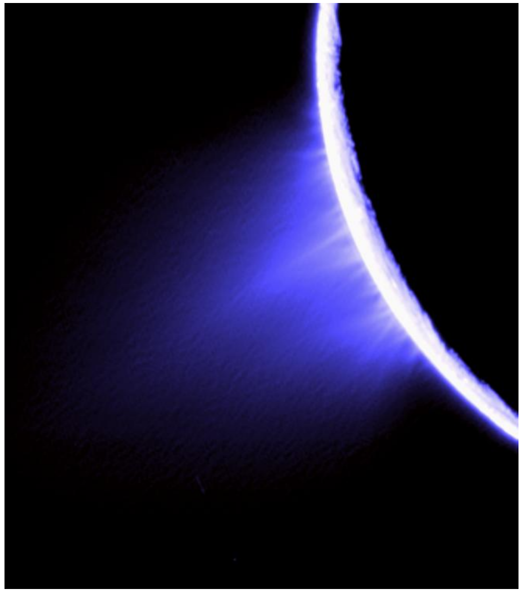
- Equatorial radius: 60,268 km (1 Rs)
- Mass: $5.68\times10^{26}$ kg
- Equatorial gravity: 10.44 $m/s^2$
- Rotation period: 0.436 day
- Revolution period: 29.46 year
- Magnetic moment: $4.6\times10^{18}$ $T/m^3$
- Tilt of magnetic axis respect to rotational axis: < 1°
- Satellites#: 64
- Rings: D, C, B, A, F, G and E
- Exploration of Saturn: Pioneer 11, Voyager 1 and 2, Cassini

Saturn’s system [*NASA/JPL*]

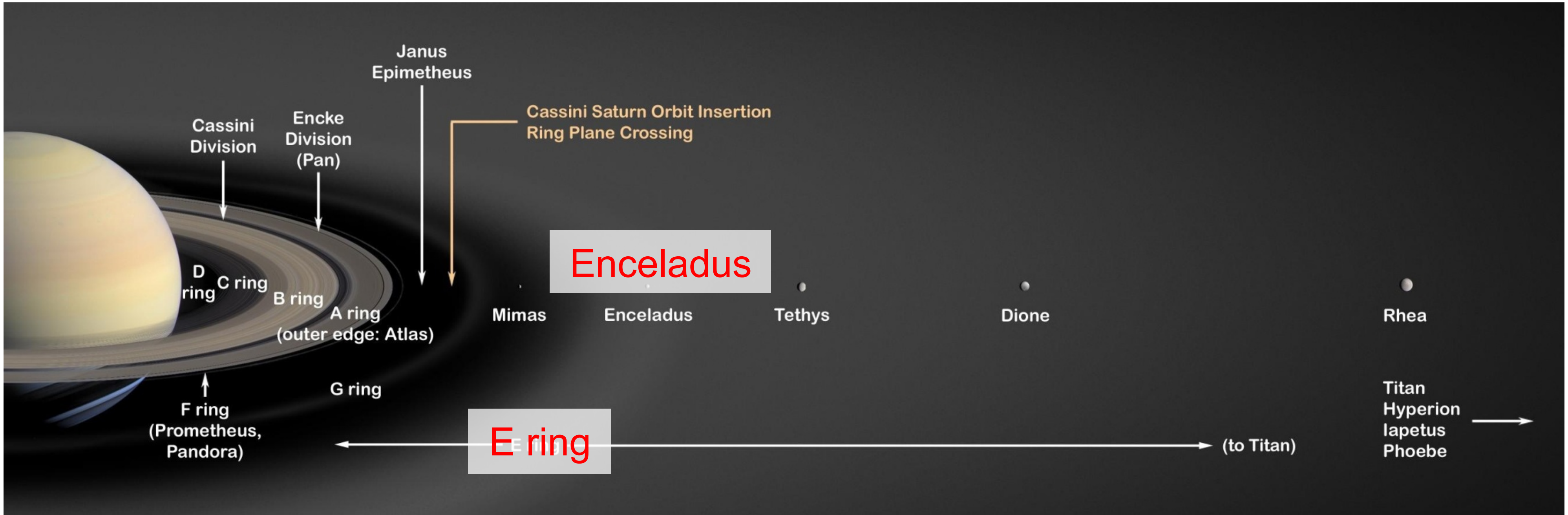


# Enceladus plume & E ring

- Enceladus plume (~3.95 Rs)
  - Water gas
- E ring
  - 3 – 8 Rs
  - Water group ion
  - Dust
  - Source: Mainly Enceladus plume
  - Kepler motion



Enceladus & E ring [*NASA/JPL*]



# Saturn’s magnetosphere

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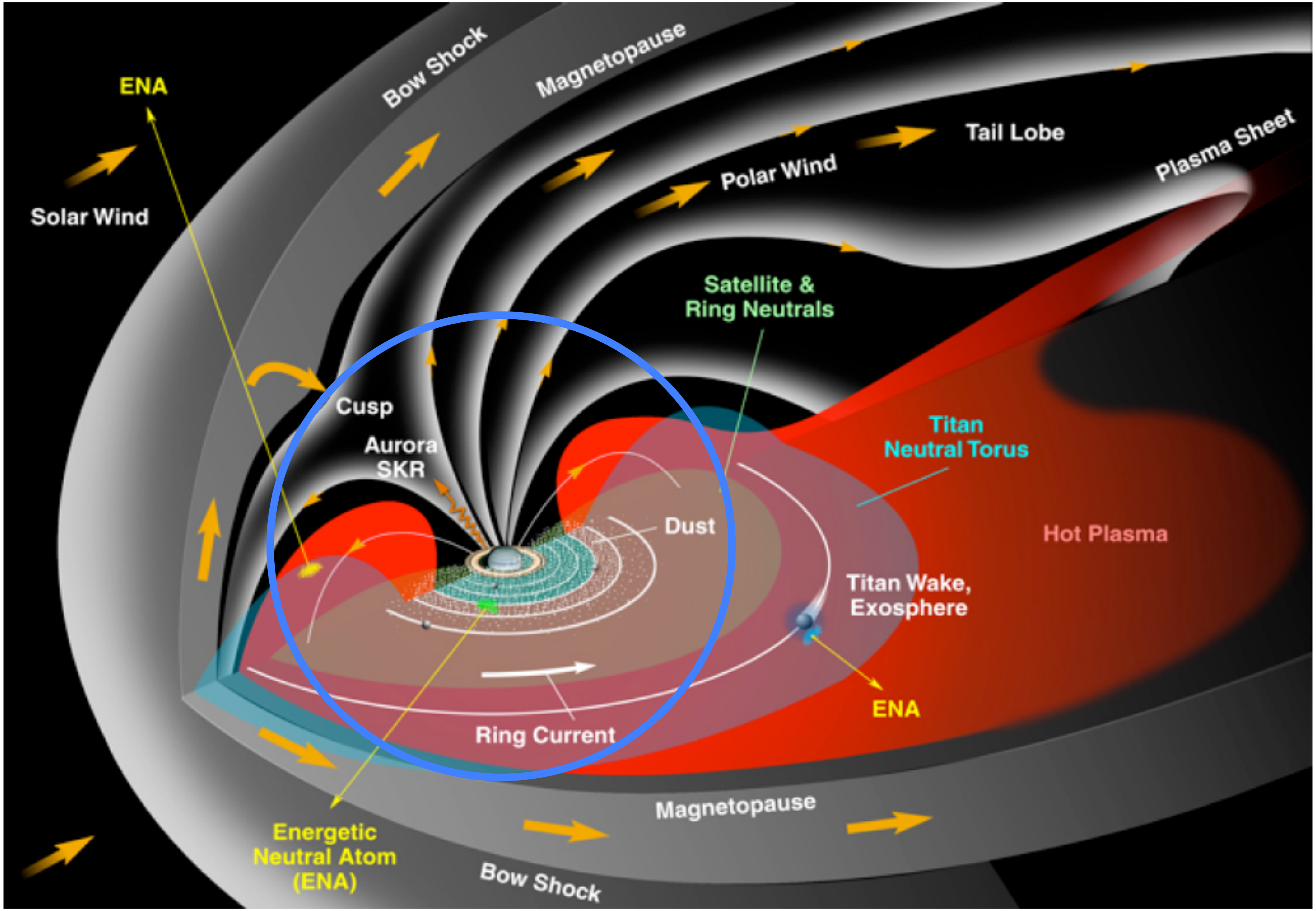
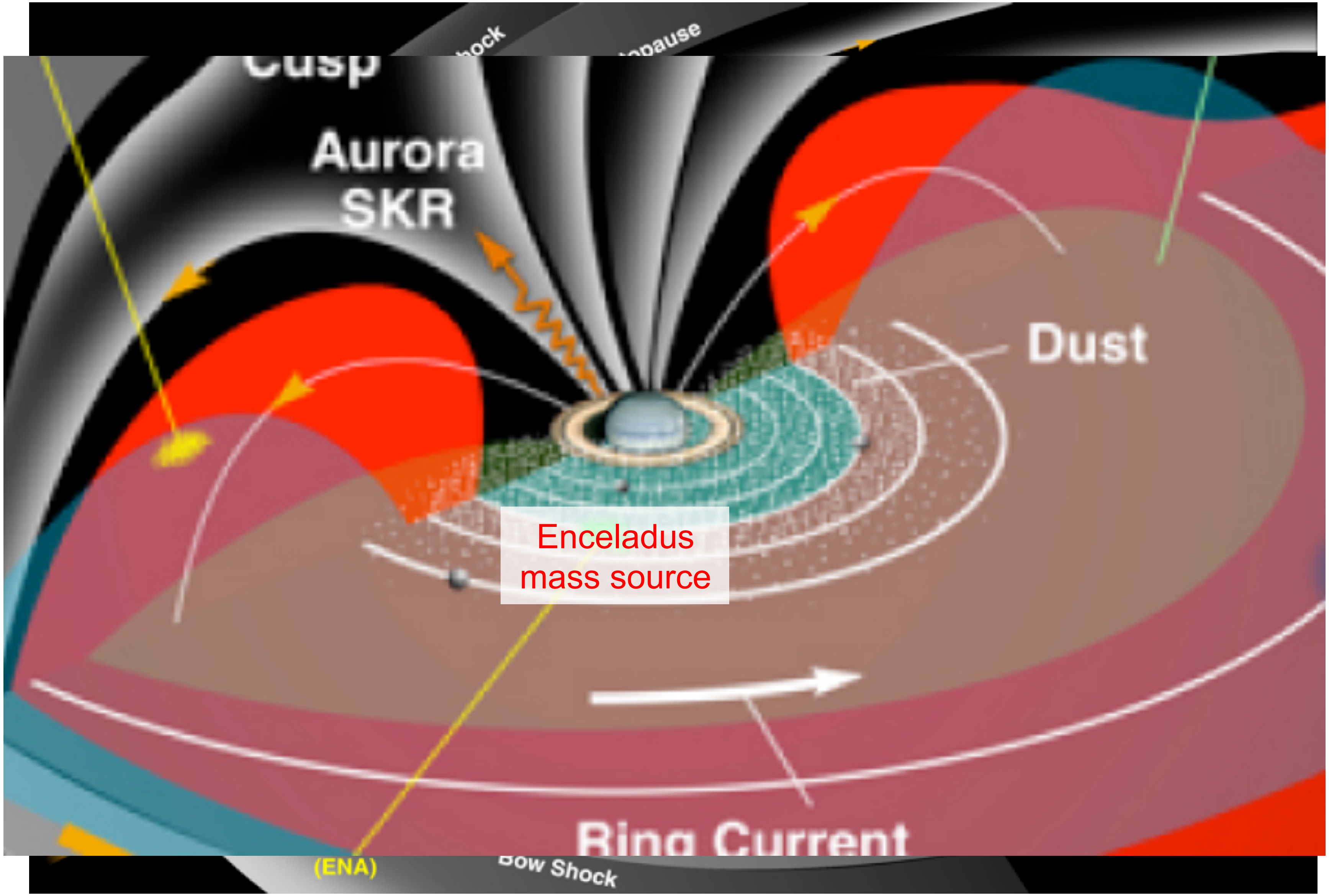


Courtesy of the Cassini MIMI team

# Saturn’s magnetosphere



Enceladus mass source

Courtesy of the Cassini MIMI team

# Why Saturn?

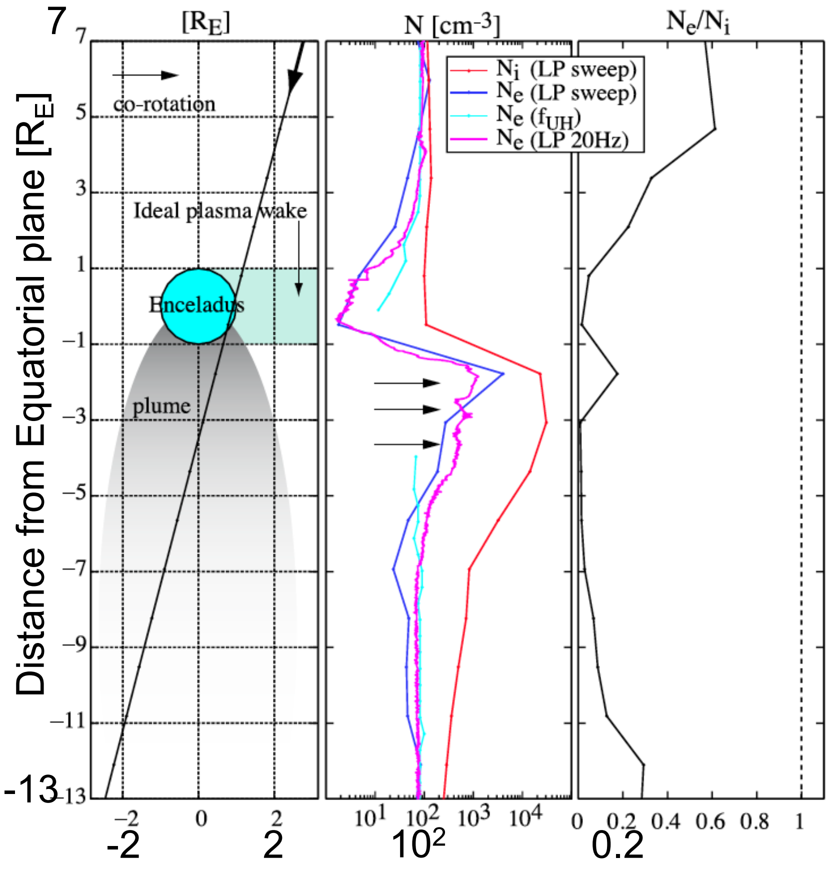
- Quite different from Earth’s magnetosphere
  - Source of plasma
    - Satellites and rings [*Moncuquet et al.*, 2005; *Persoonet al.*., 2005; *Wahlund et al.*, 2005; *Sittler et al.*, 2006]
      - Enceladus plume [*Porco et al.*, 2006; *Waite et al.*, 2006]
  - Dust
    - Charged dust of E ring from satellites [*Wahlund et al.*, 2005, 2009]
- Also different from Jovian magnetosphere
  - Dust is also existence [*Johnson et al.*, 1980; *Morfill et al.*, 1980].
  - Acceleration of dust by the magnetic force [*Horányi et al.*, 1993]
    - Strong magnetic field (200 times than Saturn’s)

→ Plasma can affect dust in Saturn’s magnetosphere!!

- Because of smaller magnetic field

# Electron depletion

- Electron depletion
  - $N_i > N_e$
    - $N_e/N_i < 1\%$ [*Morooka et al.*, 2011].
    - Negatively charged dust? [*Wahlund et al.*, 2009; *Morooka et al.*, 2011]

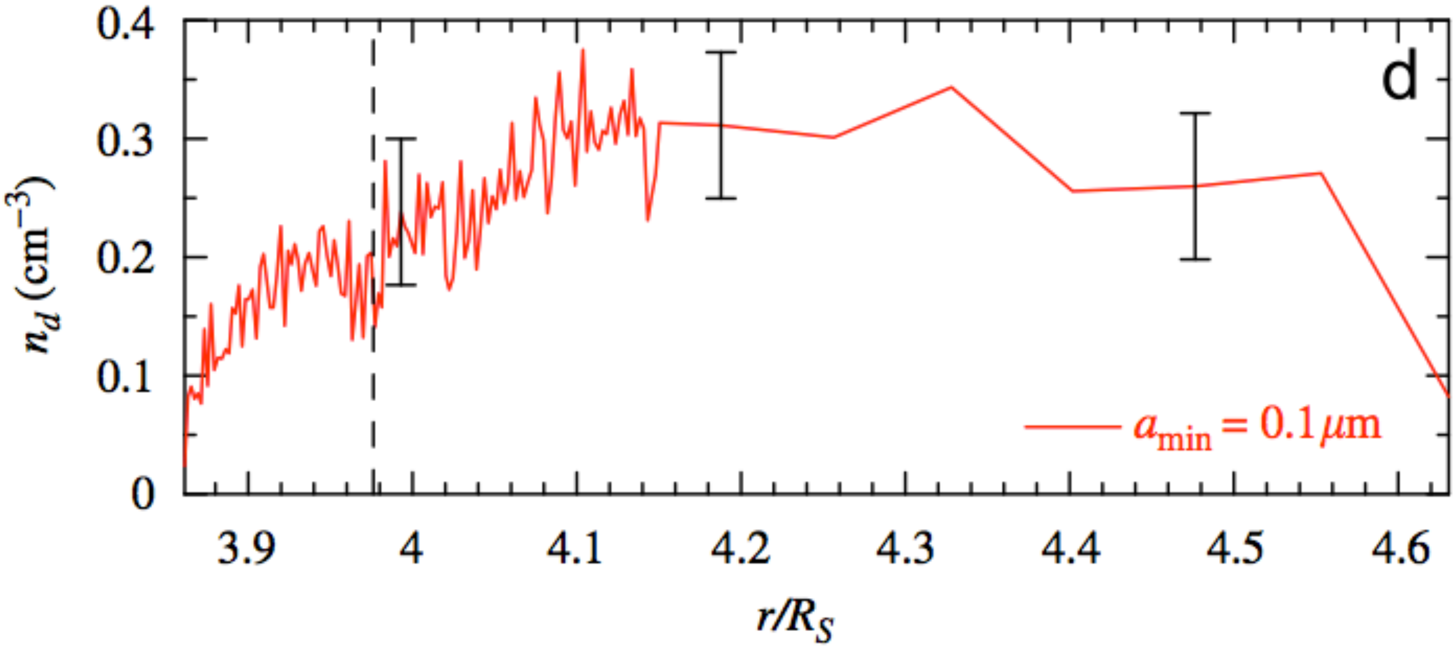


E03 Density profile [*Morooka et al.*, 2011]

# Dusts around Enceladus

- Total dust density: $10^4$—$10^7$ m$^{-3}$

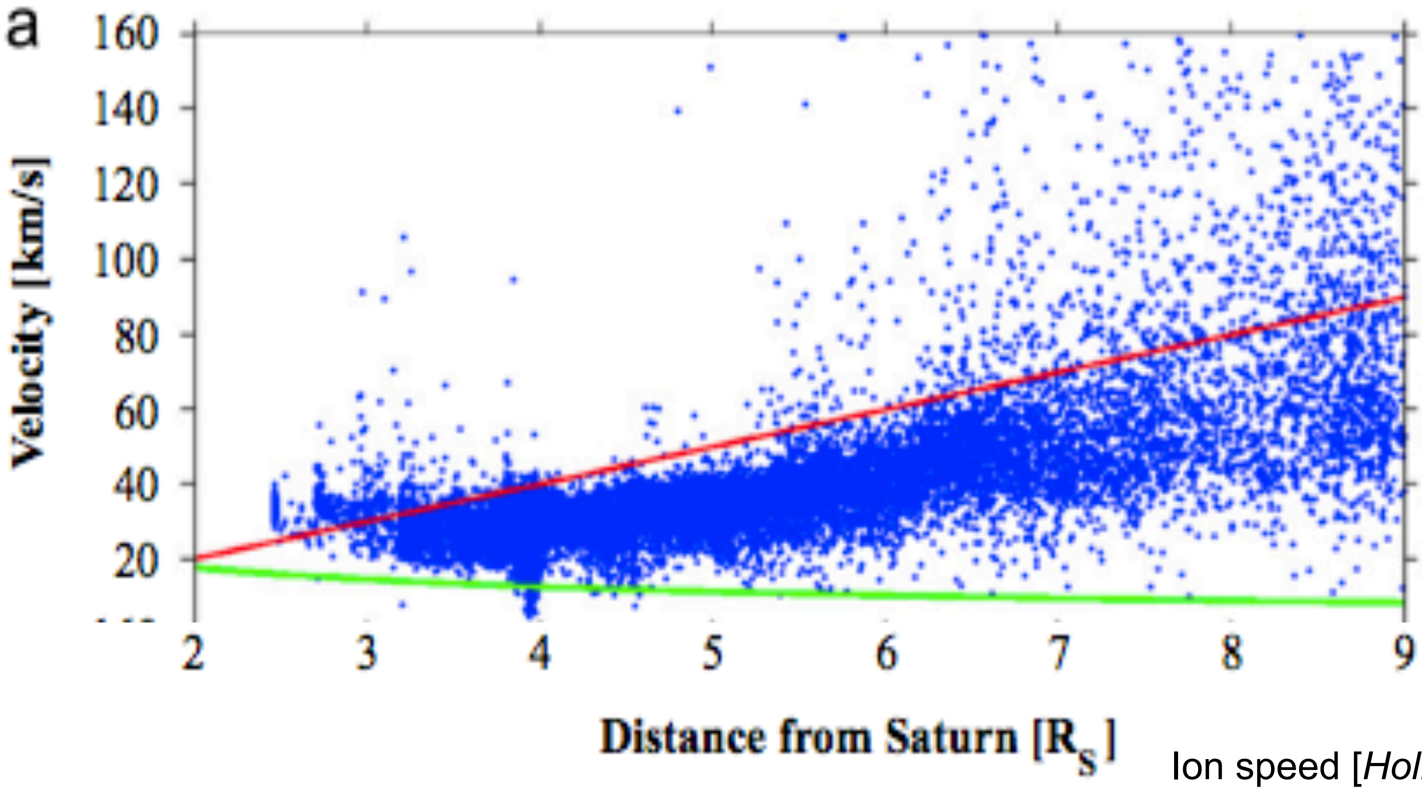
$$n_{dtot} = \int_{r_{\min}}^{r_{\max}} n_d(r_d)dr_d \approx \frac{e(n_i - n_e)}{4\pi\varepsilon_0 U_{SC}} \frac{2-\mu}{1-\mu} \frac{1}{r_{\min}}$$



Total dust density (E02) [*Yaroshenko et al,* 2009]

# Co-rotation deviation by dusts?

- Ion observations from the Cassini RPWS/LP in Saturn’s magnetosphere
  - $V_i < V_{cor}$ [*Wahlund et al.*, 2009; *Morooka et al.*, 2011; *Holmberg et al.*, 2012].



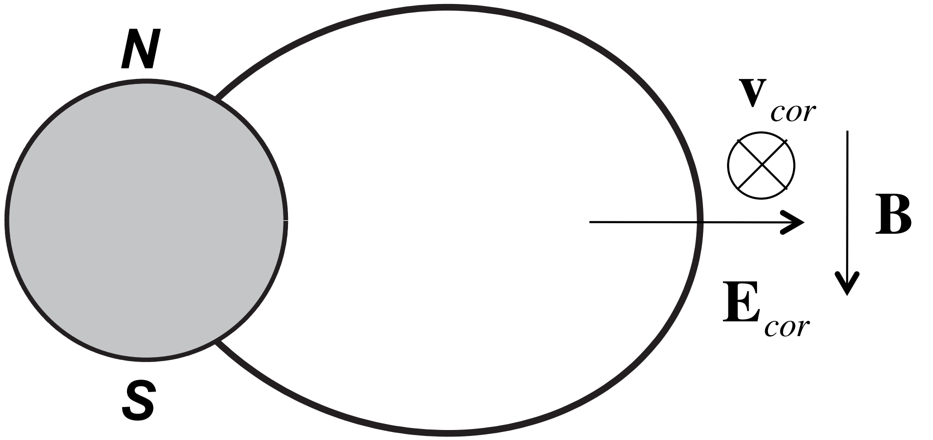
Ion speed [*Holmberg et al.*, 2012]

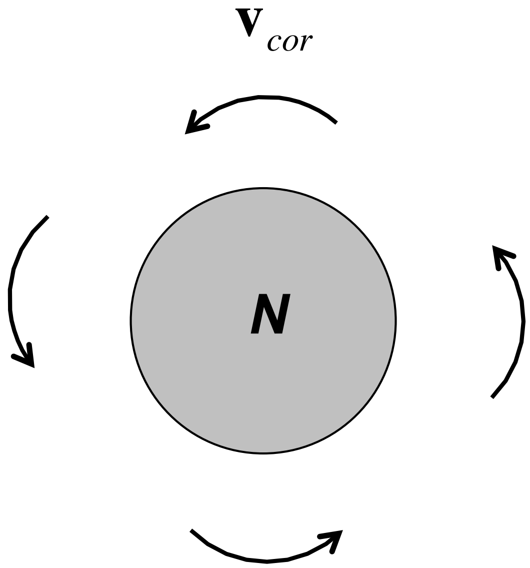
# Co-rotation

- Magnetospheric plasma should be co-rotating.

Co-rotation velocity: $\mathbf{v}_{cor} = \dfrac{\mathbf{E}_{cor} \times \mathbf{B}}{B^2}$

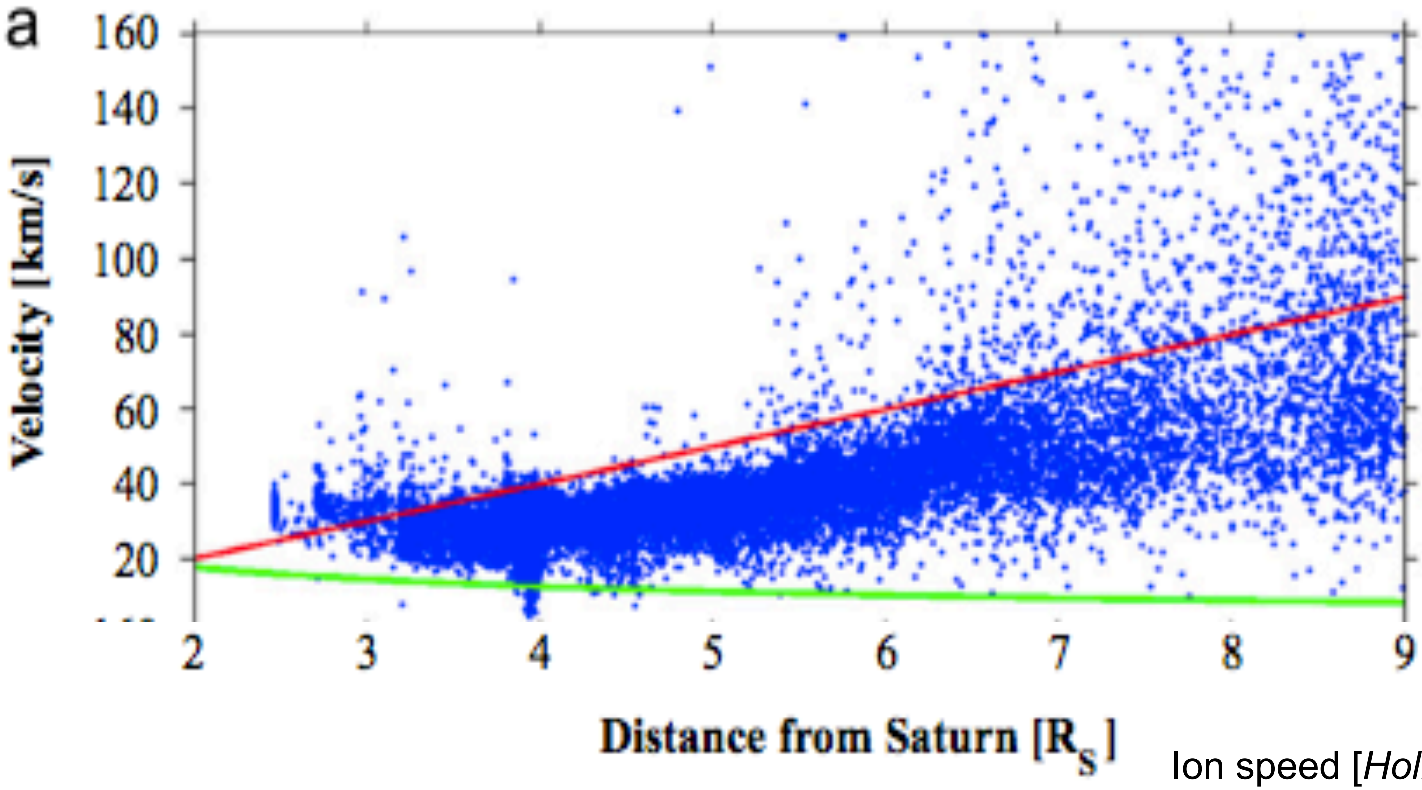
Saturn's case





# Co-rotation deviation by dusts?

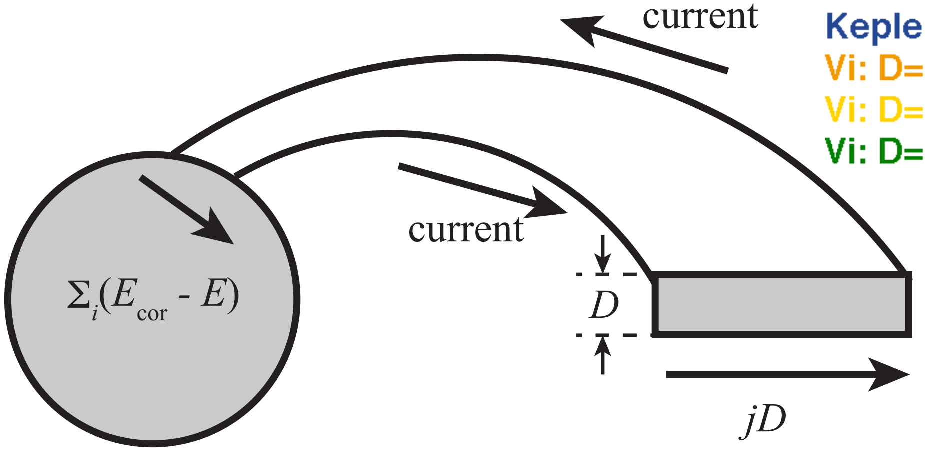
- Ion observations from the Cassini RPWS/LP in Saturn's magnetosphere
  - $V_i < V_{cor}$ [*Wahlund et al.*, 2009; *Morooka et al.*, 2011; *Holmberg et al.*, 2012].
    - Dusts affect $V_i$ in the inner magnetosphere?



Ion speed [*Holmberg et al.*, 2012]

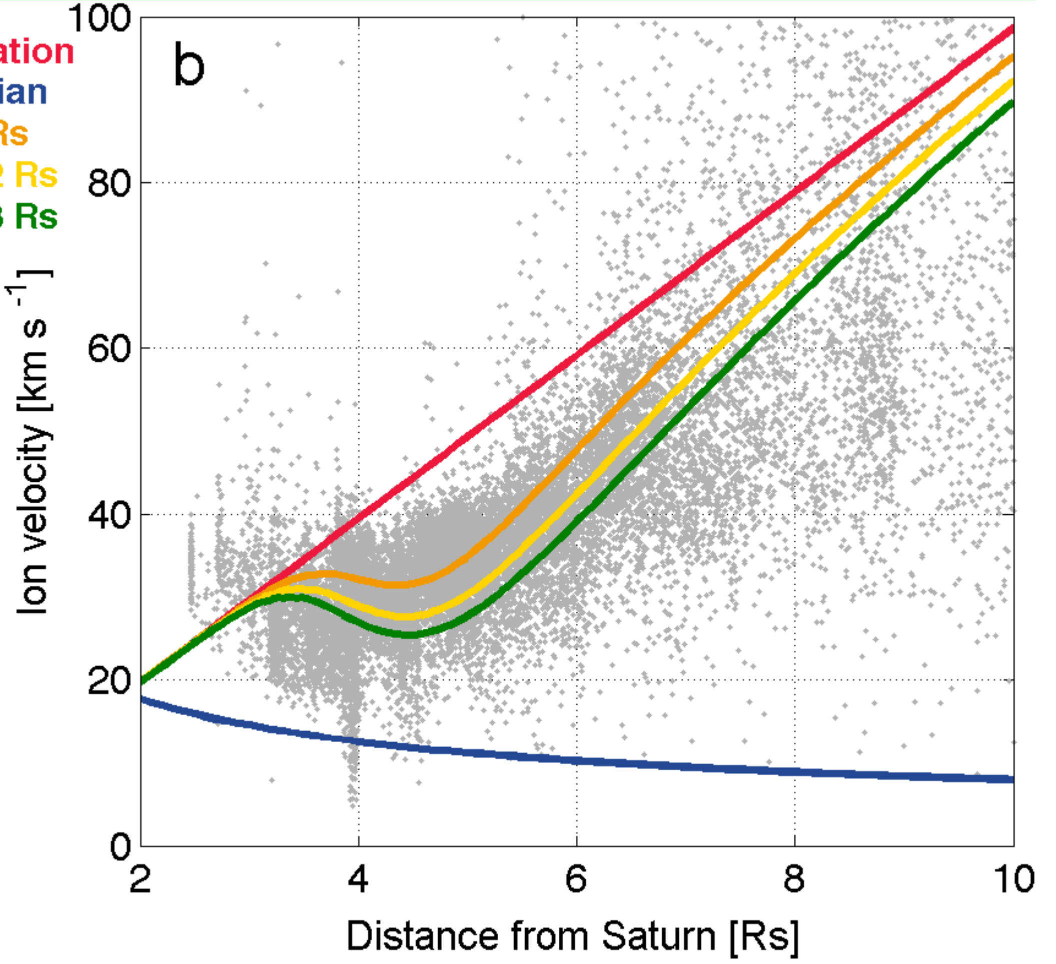
# Comparison with LP observation

$$\rho_k \frac{\partial \mathbf{v}_k}{\partial t} + \rho_k\left(\mathbf{v}_k \cdot \nabla\right)\mathbf{v}_k = n_k q_k\left(\boxed{\mathbf{E}} + \mathbf{v}_k \times \mathbf{B}\right) - \nabla p_k - \rho_k \mathbf{g} + \sum_l \rho_k \nu_{kl}\left(\mathbf{v}_k - \mathbf{v}_l\right) - \sum_l S_{k,l}\left(\mathbf{v}_k - \mathbf{v}_l\right)$$



$$\boxed{\Sigma_i}\left(\mathbf{E}_{cor} - \boxed{\mathbf{E}}\right) = \mathbf{j}D$$

- $\mathbf{j}_{\mathrm{mag,tot}}$ weakens **E**.



Magnetospheric ion velocity [*Sakai et al.*, 2013]

# Inner magnetospheric model

- Momentum equations
  - $H^+$, $H_2O^+$, $e^-$ and dust

$$\rho_k \frac{\partial \mathbf{v}_k}{\partial t} + \rho_k(\mathbf{v}_k \cdot \nabla)\mathbf{v}_k = n_k q_k(\boxed{\mathbf{E}} + \mathbf{v}_k \times \mathbf{B}) - \nabla p_k - \rho_k \mathbf{g} + \boxed{\sum_l \rho_k \nu_{kl}(\mathbf{v}_k - \mathbf{v}_l)} - \boxed{\sum_l S_{k,l}(\mathbf{v}_k - \mathbf{v}_l)}$$

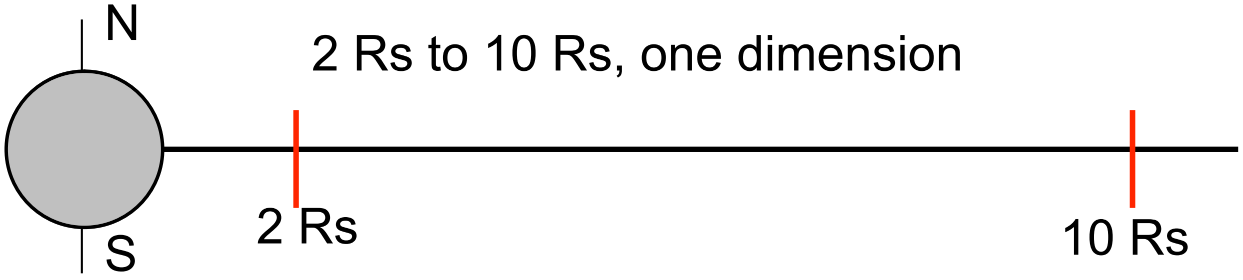
Electric field

Collision term

Chemical term

- Dust: $q_d = 4\pi\varepsilon_0 r_d \phi$
  - $r_d$ = 100 nm; $\phi$ = -2 V

| | |
|---|---|
| $S_k$ | Production rate |
| $n_k$ | Number density |
| $\mathbf{B}$ | Magnetic field |
| $q_d$ | Charge quantity of dust |
| $r_d$ | Dust radius |
| $\phi$ | Dust surface potential |
| $\varepsilon_0$ | Permittivity |



2 Rs to 10 Rs, one dimension

| | |
|---|---|
| $\mathbf{v}_k$ | Velocity |
| $\mathbf{E}$ | Electric field |
| $\mathbf{g}$ | Gravity |
| $\rho_k$ | Mass density |
| $p$ | Pressure |
| $e$ | Charge quantity |
| $\nu_{kl}$ | Collision frequency |

# Electric field

|  |  |
|---|---|
| $\mathbf{j}$ | Current density |
| $\mathbf{E}_{cor}$ | Co-rotational Electric field |
| $\Sigma_i$ | Ionospheric conductivity |
| $D$ | Thickness of dust |
| $v_{thk}$ | Thermal velocity |

- M-I coupling for deriving electric field, E

$$\Sigma_i\left(\mathbf{E}_{cor} - \mathbf{E}\right) = \mathbf{j}D$$

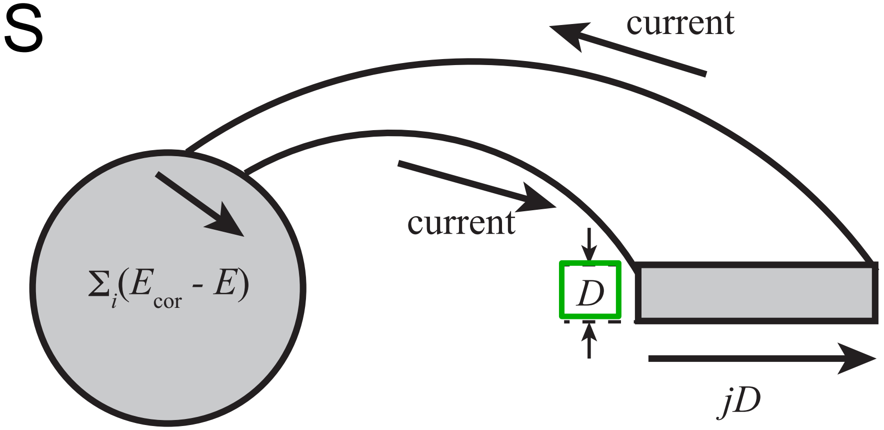
$$\mathbf{j} = en_i\mathbf{v}_i - en_e\mathbf{v}_e - q_d n_d \mathbf{v}_d$$

↓ ↓ ↓

$$\mathbf{E} = \mathbf{E}_{cor} - \frac{\mathbf{j}\boxed{D}}{\Sigma_i}$$

Thickness of dust distribution

- Ionospheric conductivity $\Sigma_i$: 1 S



# Comparison with LP observation

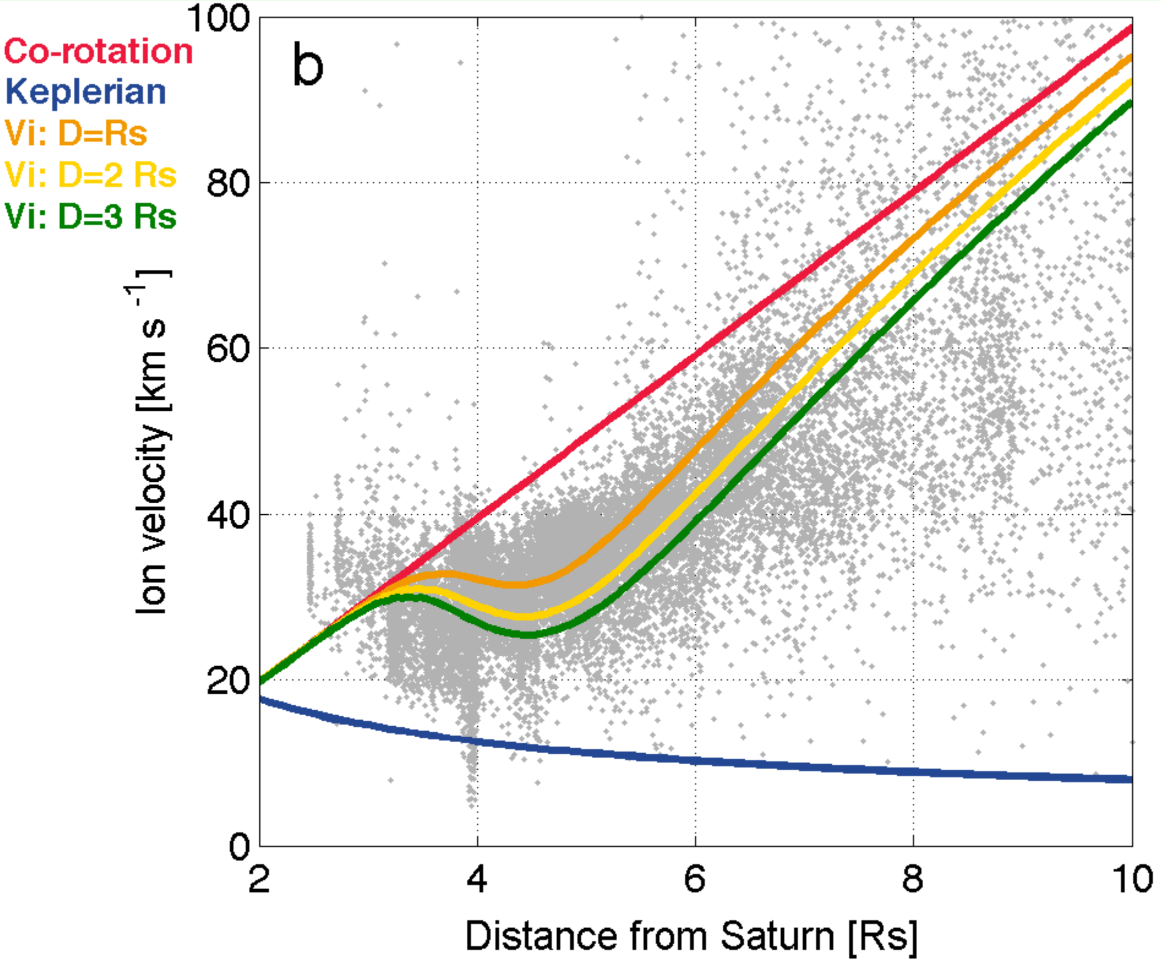
$$\rho_k \frac{\partial \mathbf{v}_k}{\partial t} + \rho_k\left(\mathbf{v}_k \cdot \nabla\right)\mathbf{v}_k = n_k q_k\left(\boxed{\mathbf{E}} + \mathbf{v}_k \times \mathbf{B}\right) - \nabla p_k - \rho_k \mathbf{g} + \sum_l \rho_k \nu_{kl}\left(\mathbf{v}_k - \mathbf{v}_l\right) - \sum_l S_{k,l}\left(\mathbf{v}_k - \mathbf{v}_l\right)$$

$$\mathbf{E} = \mathbf{E}_{cor} - \frac{\mathbf{j}D}{\Sigma_i}$$

$$\mathbf{v}_i \approx \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$$< \mathbf{v}_{cor}$$

- $\mathbf{j}_{\text{mag,tot}}$ weakens **E**.



Magnetospheric ion velocity [*Sakai et al.*, 2013]

# Comparison with LP observation

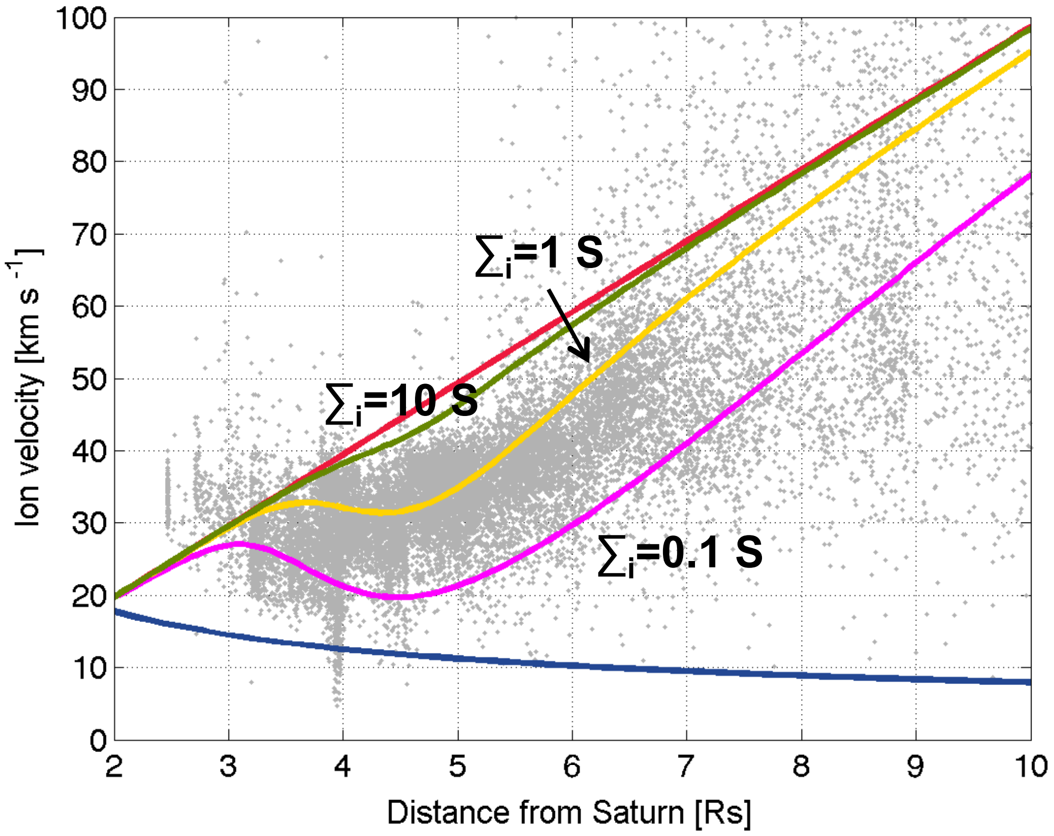
$$\rho_k \frac{\partial \mathbf{v}_k}{\partial t} + \rho_k\left(\mathbf{v}_k \cdot \nabla\right)\mathbf{v}_k = n_k q_k\left(\boxed{\mathbf{E}} + \mathbf{v}_k \times \mathbf{B}\right) - \nabla p_k - \rho_k \mathbf{g} + \sum_l \rho_k \nu_{kl}\left(\mathbf{v}_k - \mathbf{v}_l\right) - \sum_l S_{k,l}\left(\mathbf{v}_k - \mathbf{v}_l\right)$$

$$\mathbf{E} = \mathbf{E}_{cor} - \frac{\mathbf{j}D}{\boxed{\Sigma_i}}$$

$$\mathbf{v}_i \approx \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$$< \mathbf{v}_{cor}$$

- 3 cases for $\sum_i$
  - 0.1 S
  - 1 S
  - 10 S



- $V_i$ is slower when $\sum_i$ is smaller.
- $V_i$ strongly depends on $\sum_i$.

# Co-rotation deviation by dusts?

- Ionospheric Pedersen conductivity
  - E depends on the conductivity.

$$\rho_k \frac{\partial \mathbf{v}_k}{\partial t} + \rho_k \left( \mathbf{v}_k \cdot \nabla \right) \mathbf{v}_k = n_k q_k \left( \boxed{\mathbf{E}} + \mathbf{v}_k \times \mathbf{B} \right) - \nabla p_k - \rho_k \mathbf{g} + \sum_l \rho_k \nu_{kl} \left( \mathbf{v}_k - \mathbf{v}_l \right) - \sum_l S_{k,l} \left( \mathbf{v}_k - \mathbf{v}_l \right)$$

Electric field

$$\boxed{\Sigma_i} \left( \mathbf{E}_{cor} - \boxed{\mathbf{E}} \right) = \mathbf{j} D$$

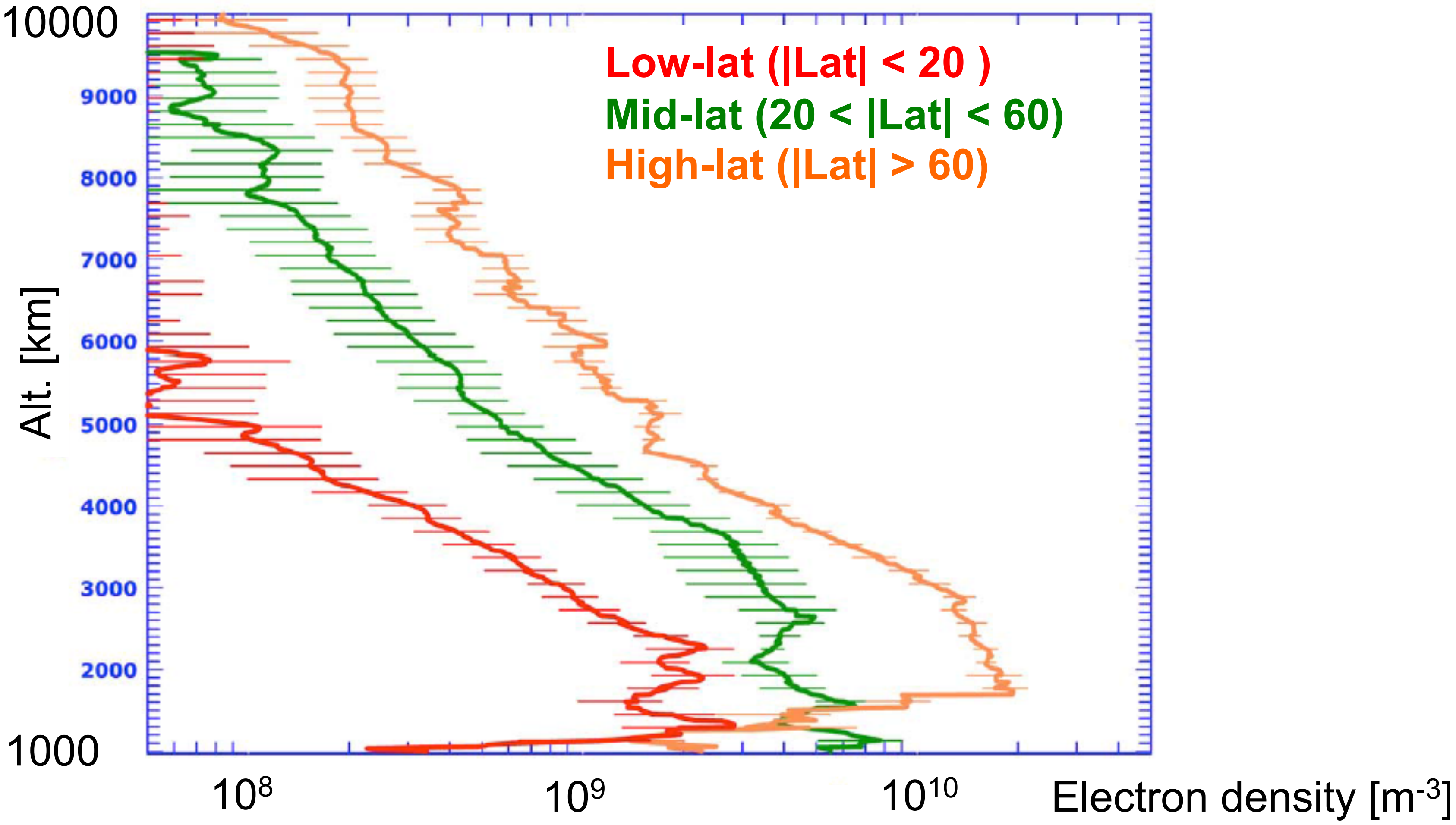
Pedersen conductivity

$$\sigma_p = \sum_i \frac{\nu_i}{\nu_{in}^2 + \omega_{ci}^2} \frac{n_i e^2}{m_i} + \frac{\nu_e}{\nu_{en}^2 + \omega_{ce}^2} \frac{n_e e^2}{m_e} \qquad \Sigma_i = \int_{z_1}^{z_2} \sigma_p \, ds$$

- One of the open questions.
  - ~0.1-100 S [*Connerney et al.*, 1983; *Cheng and Waite*, 1988]
  - ~0.02 S [*Saur et al.*, 2004]
  - 1--10 S [*Cowley et al.*, 2004; *Moore et al.*, 2010]
- Estimate the ionospheric $N_i$ for deriving $\sum_i$.

# Saturn’s ionosphere

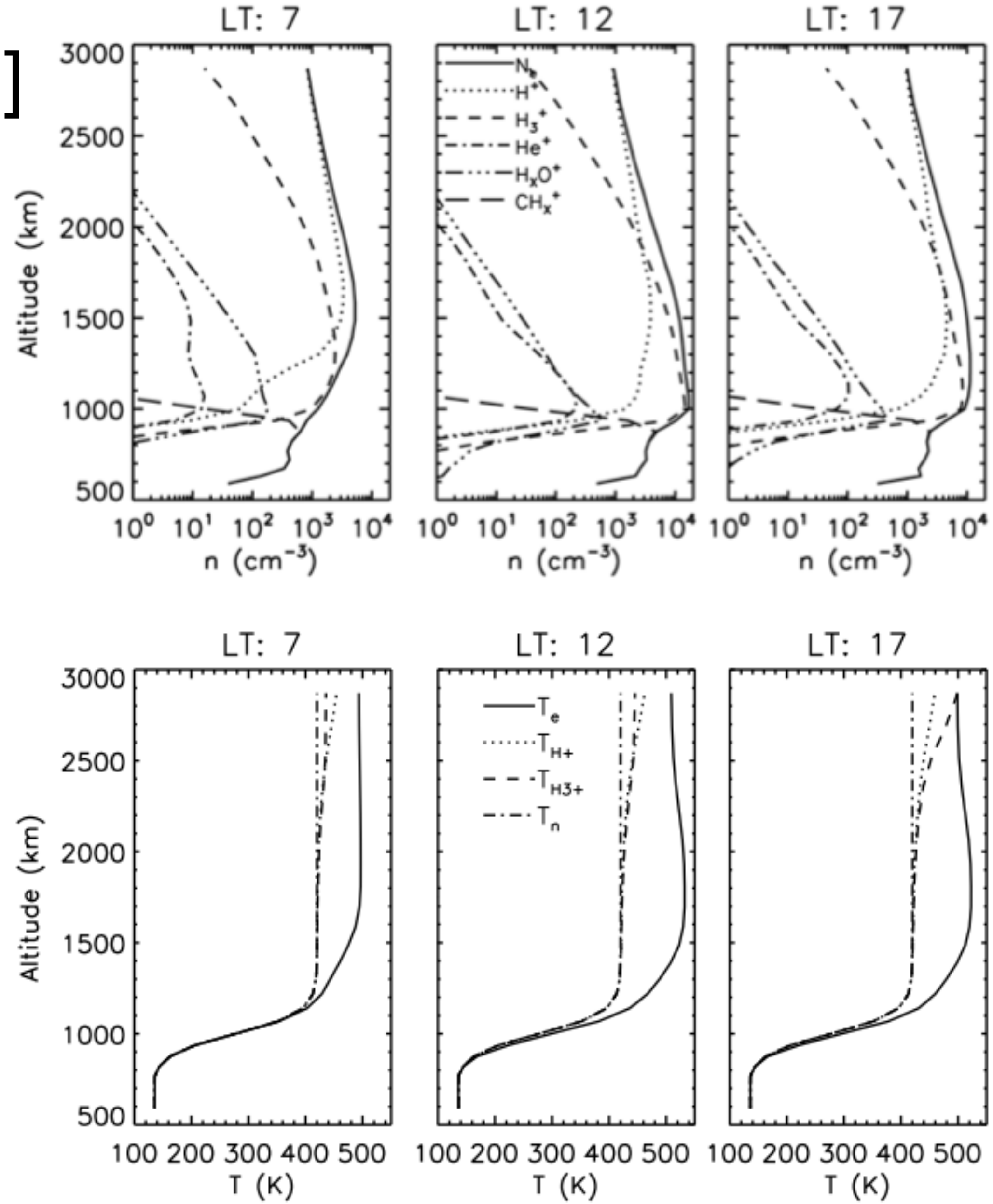
- $N_e$ observation from Cassini occultations
  - $N_e$ (average between dusk and dawn)
    - Peak density: ~$10^{10}$ $m^{-3}$; Peak alt.: ~1200 km



Electron density by occultations [*Kliore et al.*, 2009]

# Saturn’s ionosphere

- Model [*Moore et al.* 2008]
  - $N_e$
    - Average peak density: ~$10^{10}$ $m^{-3}$
    - Peak alt.: ~1200 km
  - $T_e$
    - Max: 500 K
    - Alt.: > 1500 km
- Only below ~3000 km
  - Magnetospheric effect?



Plasma density and temperature by modeling [*Moore et al.*, 2008]

# Purpose

- Construction of an ionospheric model including the inner magnetosphere.
- Estimation of the ionospheric Pedersen conductivity from plasma density in the Saturn’s ionosphere
- Investigation of the influence of magnetosphere to ionosphere

# Modeling of the ionosphere

# 3 dimensional ionospheric model

| | |
|---|---|
| $v_{\parallel}$ | Field-aligned Velocity |
| $E_{\parallel}$ | Electric field |
| $A$ | Magnetic flux cross-section |
| $g$ | Gravity and CF |
| $T$ | Temperature |
| $Q$ | Heating rate |
| $\kappa$ | Diffusion coefficient |

- Primitive equations
  - Ion

Density: $$\frac{\partial \rho_i}{\partial t} + \frac{1}{A}\frac{\partial \left(A\rho_i v_{i,\parallel}\right)}{\partial s} = S_i - L_i$$

Momentum: $$\rho_i \frac{\partial v_{i,\parallel}}{\partial t} + \rho_i v_{i,\parallel}\frac{\partial v_{i,\parallel}}{\partial s} = n_i e E_{\parallel} - \frac{\partial p_i}{\partial s} - \rho_i g - \sum_k \rho_i \nu_{ik}\left(v_{i,\parallel} - v_{k,\parallel}\right)$$

Temperature: $T_i = T_e$

$N_i$ ($H^+$, $H_2^+$, $H_3^+$, $He^+$, $H_2O^+$ and $H_3O^+$),

$V_i$ ($H^+$, $H_2^+$, $H_3^+$, $He^+$, $H_2O^+$ and $H_3O^+$),

$T_e$, $T_i$

  - Electron

Density: $$n_e = \sum_i n_i$$

Momentum: $$E_{\parallel} = -\frac{1}{e n_e}\frac{\partial p_e}{\partial s}$$

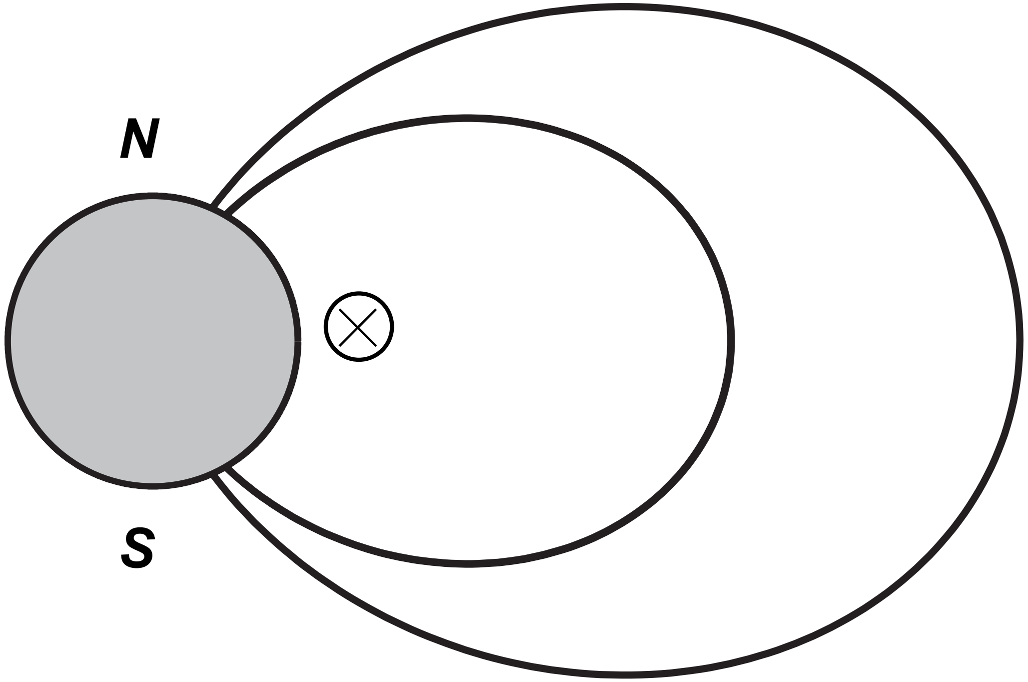
Temperature: $$\frac{\partial T_e}{\partial t} - \frac{2}{3}\frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_e \frac{\partial T_e}{\partial s}\right) = Q_{EUV} + Q_{coll} + Q_{joule} + Q_{ph,ionos} + Q_{ph,mag}$$

# Model

- Dipole coordinate system
  - Along the magnetic field line → 1 dimension

  \+ Increasing the number of magnetic field line → 2 dimensions

  \+ Time evolution → 3 dimensions



# 3 dimensional ionospheric model

| | |
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- Primitive equations
  - Ion

Source and Loss rate

Density:

$$\frac{\partial \rho_i}{\partial t} + \frac{1}{A}\frac{\partial \left(A\rho_i v_{i,\parallel}\right)}{\partial s} = \boxed{S_i - L_i}$$

Momentum:

$$\rho_i \frac{\partial v_{i,\parallel}}{\partial t} + \rho_i v_{i,\parallel}\frac{\partial v_{i,\parallel}}{\partial s} = n_i e E_\parallel - \frac{\partial p_i}{\partial s} - \rho_i g - \sum_k \rho_i \nu_{ik}\left(v_{i,\parallel} - v_{k,\parallel}\right)$$

Temperature: $T_i = T_e$

$N_i$ ($H^+$, $H_2^+$, $H_3^+$, $He^+$, $H_2O^+$ and $H_3O^+$),

$V_i$ ($H^+$, $H_2^+$, $H_3^+$, $He^+$, $H_2O^+$ and $H_3O^+$),

$T_e$, $T_i$

  - Electron

Density:

$$n_e = \sum_i n_i$$

Momentum:

$$E_\parallel = -\frac{1}{e n_e}\frac{\partial p_e}{\partial s}$$

Temperature:

$$\frac{\partial T_e}{\partial t} - \frac{2}{3}\frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_e \frac{\partial T_e}{\partial s}\right) = Q_{EUV} + Q_{coll} + Q_{joule} + Q_{ph,ionos} + Q_{ph,mag}$$

# Source & Loss

- Chemical reactions of 6 ion components
  - $H^+$, $H_2^+$, $H_3^+$, $He^+$, $H_2O^+$ and $H_3O^+$
  - 29 reactions

| Chemical reaction | Rate coefficiants | References |
|---|---|---|
| $H + h\nu \rightarrow H^+ + e^-$ | | *Moses and Bass* [2000] |
| $H_2 + h\nu \rightarrow H^+ + H + e^-$ | | *Moses and Bass* [2000] |
| $H_2 + h\nu \rightarrow H_2^+ + e^-$ | | *Moses and Bass* [2000] |
| $He + h\nu \rightarrow He^+ + e^-$ | | *Moses and Bass* [2000] |
| $H_2O + h\nu \rightarrow H^+ + OH + e^-$ | | *Moses and Bass* [2000] |
| $H_2O + h\nu \rightarrow H_2O^+ + e^-$ | | *Moses and Bass* [2000] |
| $H^+ + e^- \rightarrow H$ | $1.9 \times 10^{-16} T_e^{-0.7}$ | *Moses and Bass* [2000];<br>*Kim and Fox* [1994] |
| $H_2^+ + e^- \rightarrow H + H$ | $2.3 \times 10^{-12} T_e^{-0.4}$ | *Moses and Bass* [2000];<br>*Kim and Fox* [1994] |
| $H_3^+ + e^- \rightarrow H_2 + H$ | $7.6 \times 10^{-13} T_e^{-0.5}$ | *Moses and Bass* [2000];<br>*Kim and Fox* [1994] |
| $H_3^+ + e^- \rightarrow 3H$ | $9.7 \times 10^{-13} T_e^{-0.5}$ | *Moses and Bass* [2000];<br>*Kim and Fox* [1994] |
| $He^+ + e^- \rightarrow He$ | $1.9 \times 10^{-16} T_e^{-0.7}$ | *Moses and Bass* [2000];<br>*Kim and Fox* [1994] |
| $H_2O^+ + e^- \rightarrow O + H_2$ | $3.5 \times 10^{-12} T_e^{-0.5}$ | *Moses and Bass* [2000];<br>*Miller et al.* [1997] |
| $H_2O^+ + e^- \rightarrow OH + H$ | $2.8 \times 10^{-12} T_e^{-0.5}$ | *Moses and Bass* [2000];<br>*Miller et al.* [1997] |
| $H_3O^+ + e^- \rightarrow H_2O + H$ | $6.1 \times 10^{-12} T_e^{-0.5}$ | *Moses and Bass* [2000];<br>*Miller et al.* [1997] |
| $H_3O^+ + e^- \rightarrow OH + 2H$ | $1.1 \times 10^{-11} T_e^{-0.5}$ | *Moses and Bass* [2000];<br>*Miller et al.* [1997] |
| $H^+ + H_2 \rightarrow H_2^+ + H$ | see text | *Moses and Bass* [2000] |
| $H^+ + H_2 + M \rightarrow H_3^+ + M$ | $3.2 \times 10^{-41}$ | *Moses and Bass* [2000];<br>*Kim and Fox* [1994] |
| $H^+ + H_2O \rightarrow H_2O^+ + H$ | $8.2 \times 10^{-15}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |
| $H_2^+ + H \rightarrow H^+ + H_2$ | $6.4 \times 10^{-16}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |
| $H_2^+ + H_2 \rightarrow H_3^+ + H$ | $2.0 \times 10^{-15}$ | *Moses and Bass* [2000];<br>*Kim and Fox* [1994] |
| $H_2^+ + H_2O \rightarrow H_2O^+ + H_2$ | $3.9 \times 10^{-15}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |
| $H_2^+ + H_2O \rightarrow H_3O^+ + H$ | $3.4 \times 10^{-15}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |
| $H_3^+ + H_2O \rightarrow H_3O^+ + H_2$ | $5.3 \times 10^{-15}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |
| $He^+ + H_2 \rightarrow H^+ + H + He$ | $8.8 \times 10^{-20}$ | *Matcheva et al.* [2001];<br>*Perry* [1999] |
| $He^+ + H_2 \rightarrow H_2^+ + He$ | $9.4 \times 10^{-21}$ | *Moses and Bass* [2000];<br>*Kim and Fox* [1994] |
| $He^+ + H_2O \rightarrow H^+ + OH + He$ | $1.9 \times 10^{-16}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |
| $He^+ + H_2O \rightarrow H_2O^+ + He$ | $5.5 \times 10^{-17}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |
| $H_2O^+ + H_2 \rightarrow H_3O^+ + H$ | $7.6 \times 10^{-16}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |
| $H_2O^+ + H_2O \rightarrow H_3O^+ + OH$ | $1.9 \times 10^{-15}$ | *Moses and Bass* [2000];<br>*Anicich* [1993] |

# 3 dimensional ionospheric model

|  |  |
|---|---|
| $v_{\parallel}$ | Field-aligned Velocity |
| $E_{\parallel}$ | Electric field |
| $A$ | Magnetic flux cross-section |
| $g$ | Gravity and CF |
| $T$ | Temperature |
| $Q$ | Heating rate |
| $\kappa$ | Diffusion coefficient |

- Primitive equations
  - Ion

Source and Loss rate

Density: $$\frac{\partial \rho_i}{\partial t} + \frac{1}{A}\frac{\partial\left(A\rho_i v_{i,\parallel}\right)}{\partial s} = \boxed{S_i - L_i}$$

Momentum: $$\rho_i \frac{\partial v_{i,\parallel}}{\partial t} + \rho_i v_{i,\parallel}\frac{\partial v_{i,\parallel}}{\partial s} = n_i e E_{\parallel} - \frac{\partial p_i}{\partial s} - \rho_i g - \sum_k \rho_i \nu_{ik}\left(v_{i,\parallel} - v_{k,\parallel}\right)$$

Temperature: $T_i = T_e$

$N_i$ ($H^+$, $H_2^+$, $H_3^+$, $He^+$, $H_2O^+$ and $H_3O^+$),

$V_i$ ($H^+$, $H_2^+$, $H_3^+$, $He^+$, $H_2O^+$ and $H_3O^+$),

$T_e$, $T_i$

  - Electron

Density: $$n_e = \sum_i n_i$$

Momentum: $$E_{\parallel} = -\frac{1}{e n_e}\frac{\partial p_e}{\partial s}$$

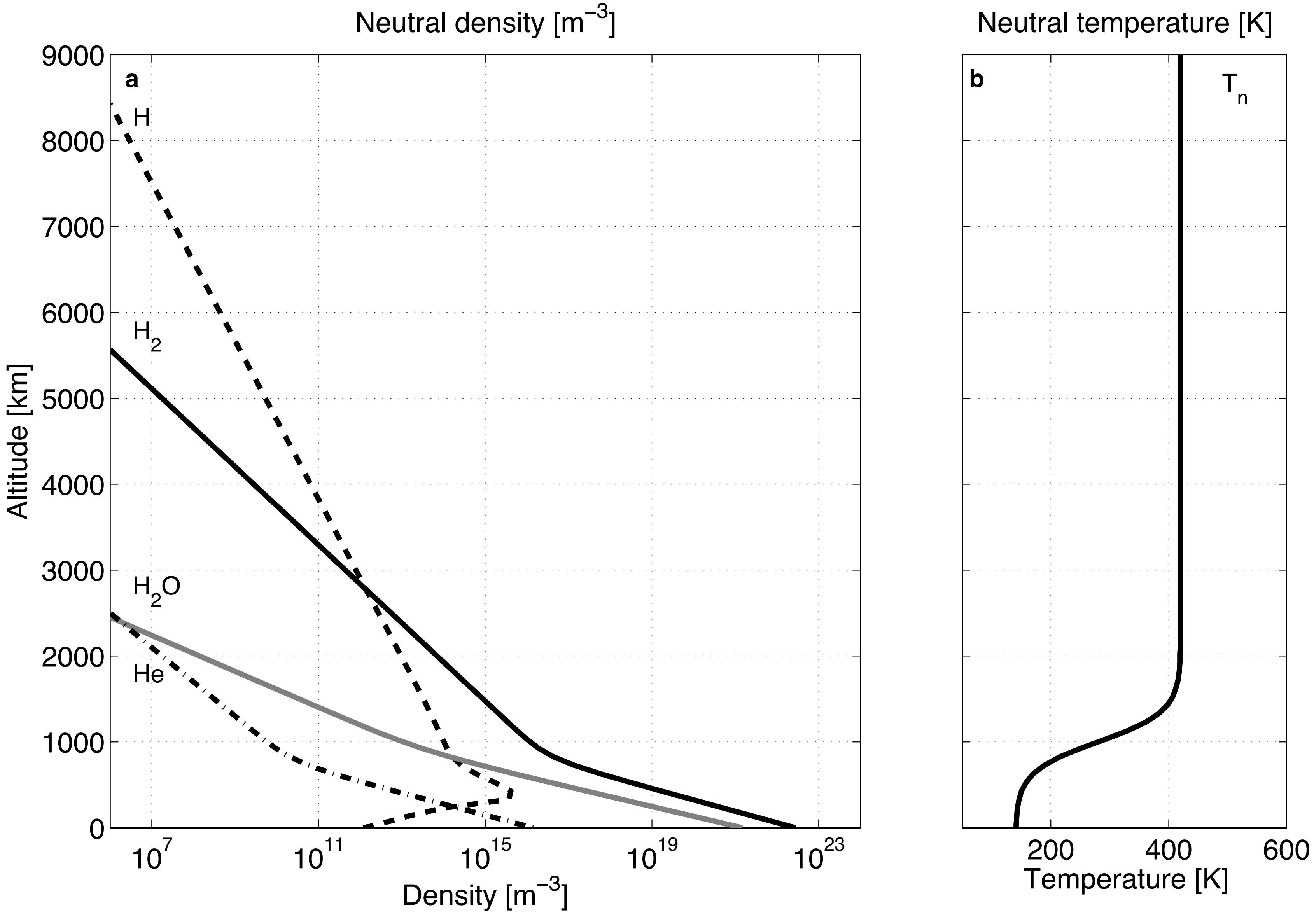
EUV, collision, Joule heating, photoelectron

Temperature: $$\frac{\partial T_e}{\partial t} - \boxed{\frac{2}{3}\frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_e \frac{\partial T_e}{\partial s}\right)} = \boxed{Q_{EUV} + Q_{coll} + Q_{joule} + Q_{ph,ionos} + Q_{ph,mag}}$$

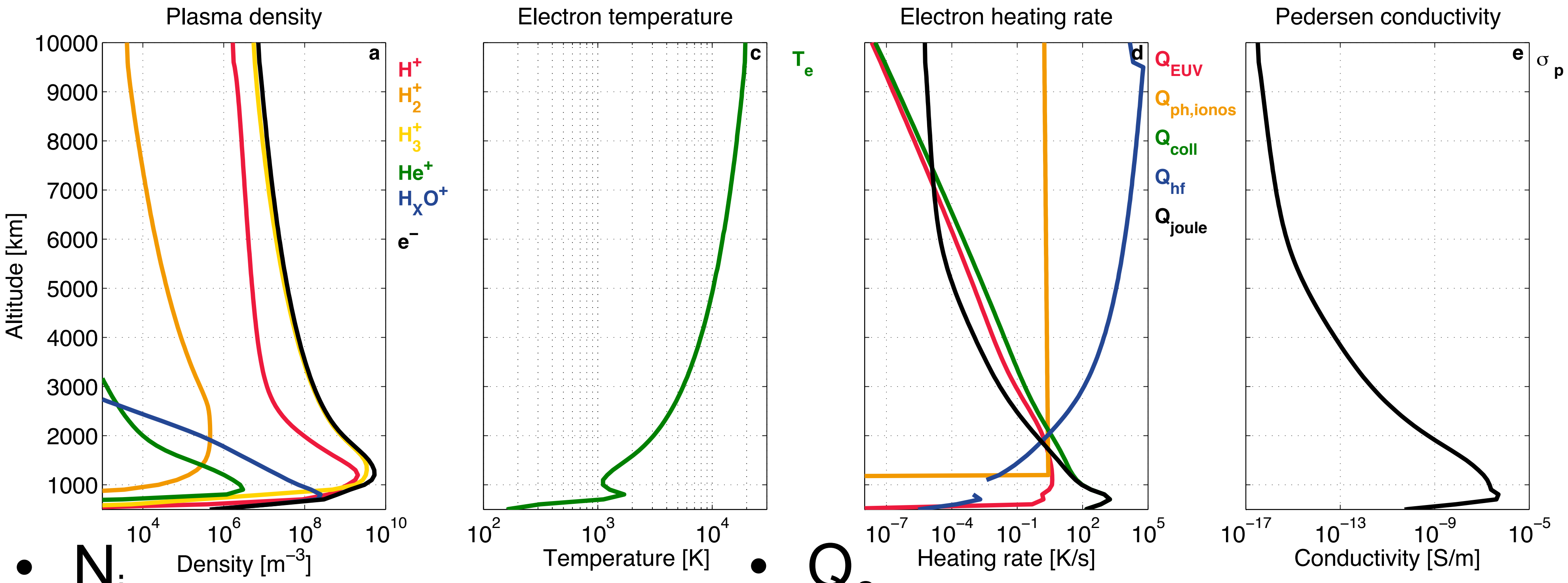
Heat flow, $Q_{HF}$

Heating rate

# Background neutral atmosphere

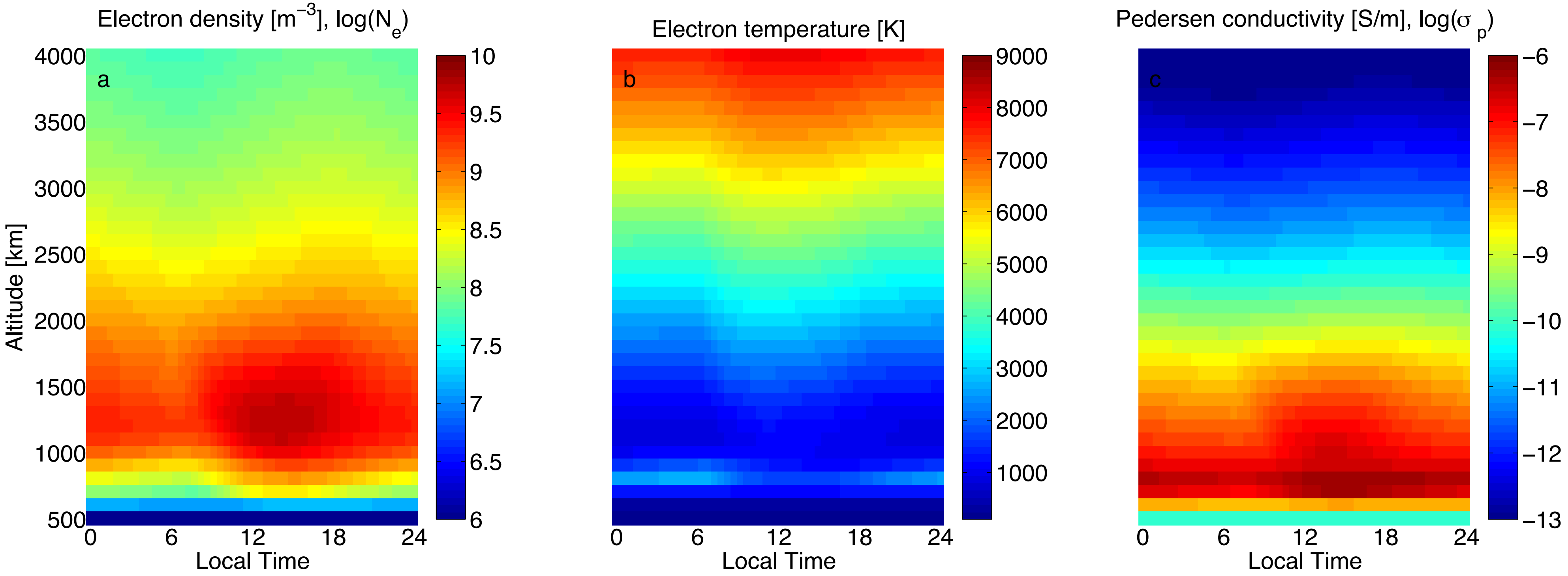


# $N_i$, $\sigma_p$, $T_e$, $Q_e$ (L=5, LT=12)



- $N_i$
  - $H_3^+$ is dominant. Max: ~$10^{10}$ $m^{-3}$
- $T_e$
  - 2000 K at ~1200 km
  - $T_e$ drastically increases.
- $Q_e$
  - $Q_{Joule}$ and $Q_{coll}$ are important at low altitude.
  - $Q_{HF}$ is contributing to heat process above topside.
- $\sigma_i$
  - Maximum around 1000 km

# Diurnal variations of $N_e$, $T_e$ and $\sigma_p$ (L=5)



- $N_e$, $\sigma_p$
  - Start to increase after 6 LT
  - Max: ~14 LT
  - $N_e$ and $\sigma_p$ decreases at high altitudes.
- $T_e$
  - Max: ~12 LT
  - $T_e$ is kept to high temperature in all LT by $Q_{HF}$.

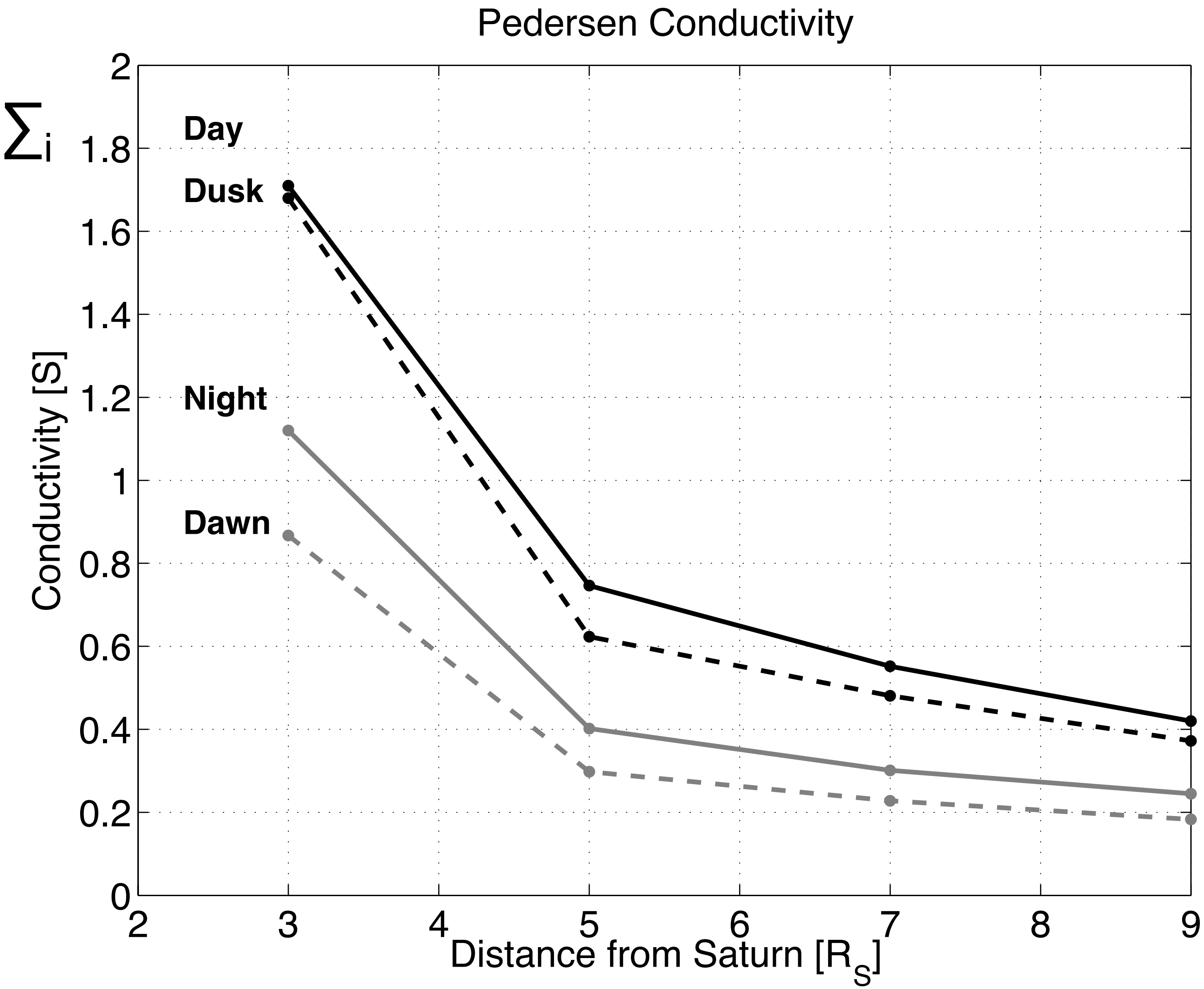
# M-I coupling

# Pedersen conductivity

$$\sigma_p = \sum_i \frac{\nu_i}{\nu_{in}^2 + \omega_{ci}^2} \frac{n_i e^2}{m_i} + \frac{\nu_e}{\nu_{en}^2 + \omega_{ce}^2} \frac{n_e e^2}{m_e}$$

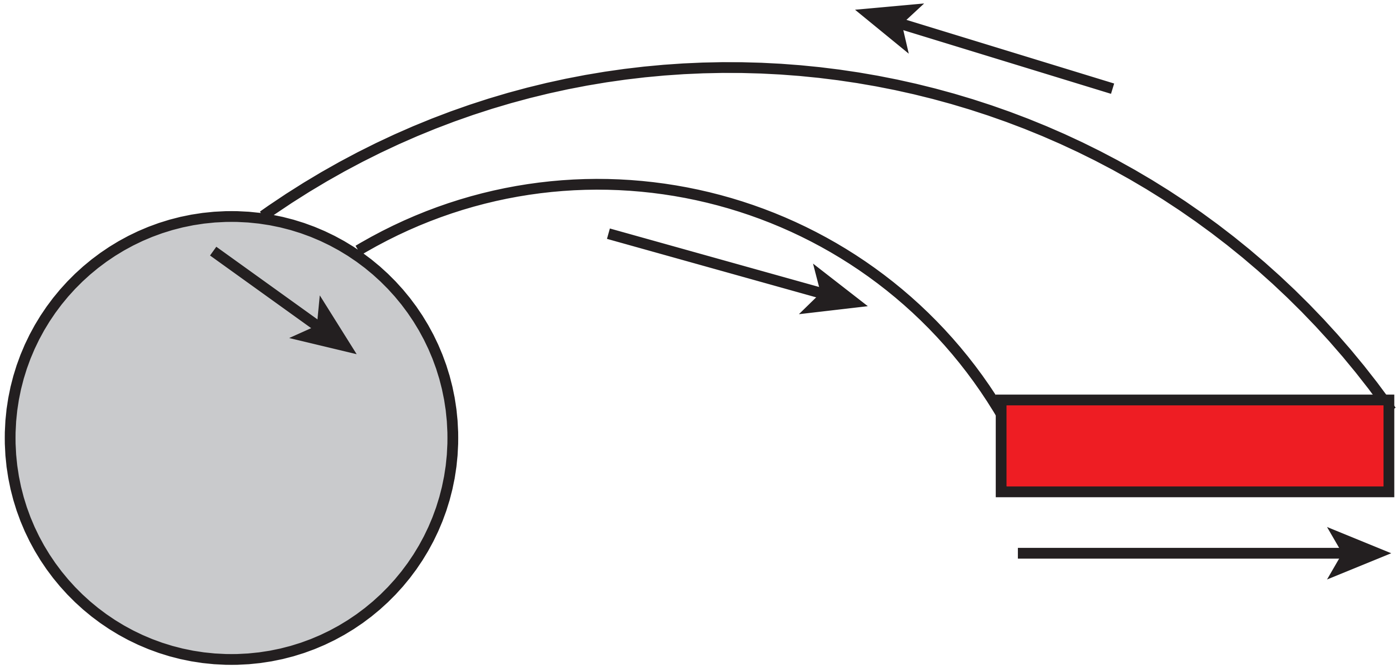
$$\boxed{\Sigma_i = \int_{z_1}^{z_2} \sigma_p ds}$$

- LT dependence of $\sum_i$
- $\sum_i$ decreases with increase of Rs



# Magnetospheric ion velocity

1. Modeling of inner magnetosphere with dust-plasma interaction
2. Modeling of ionosphere
3. Magnetosphere-ionosphere coupling



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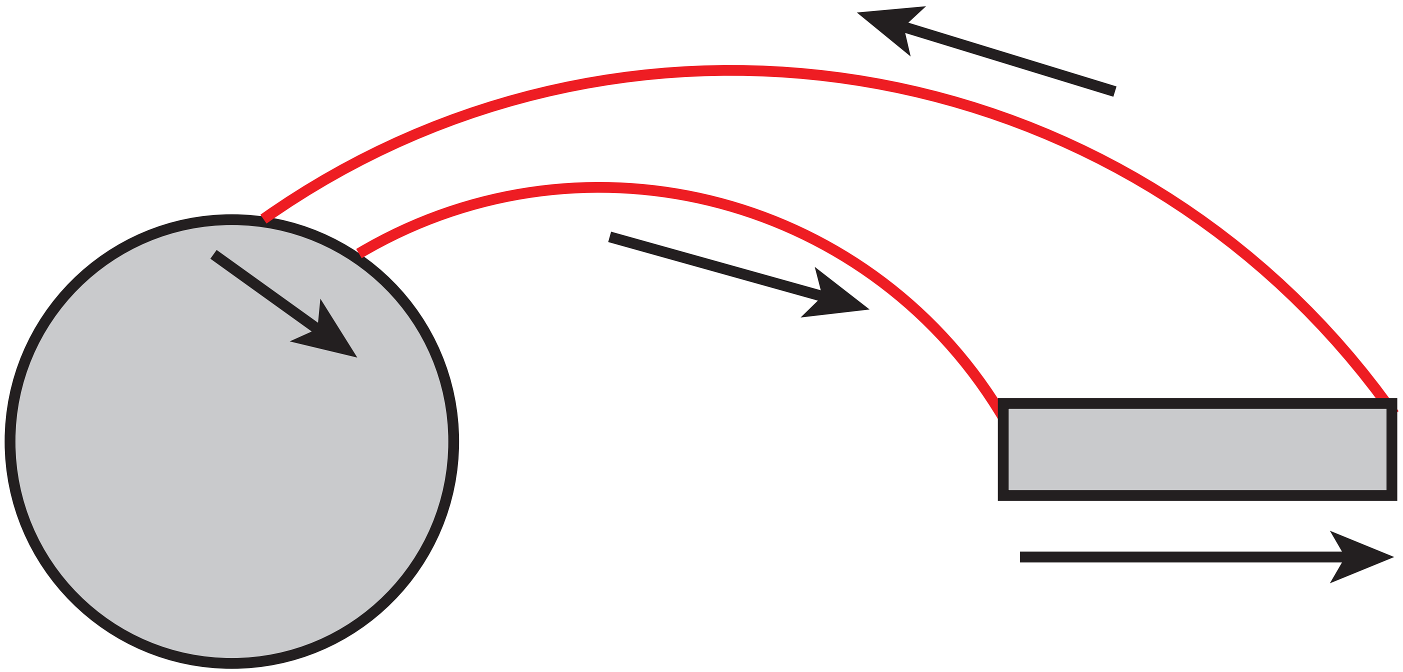

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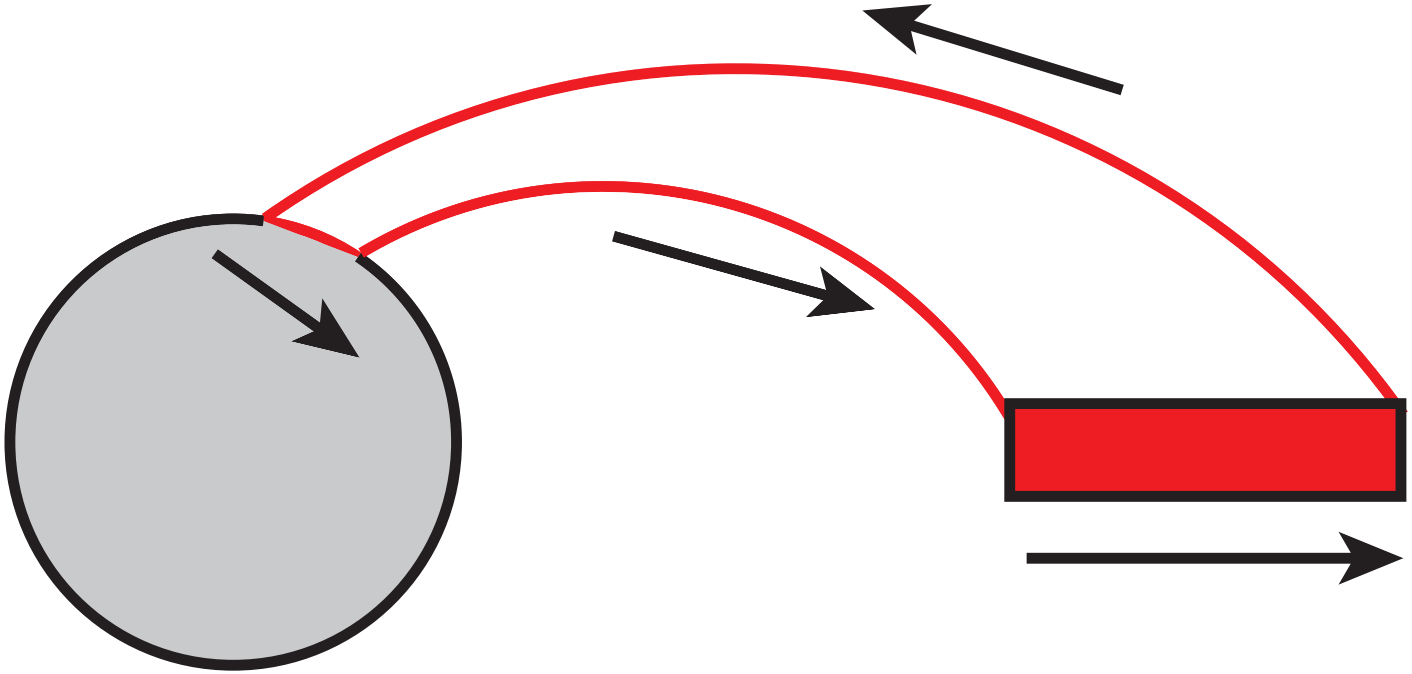
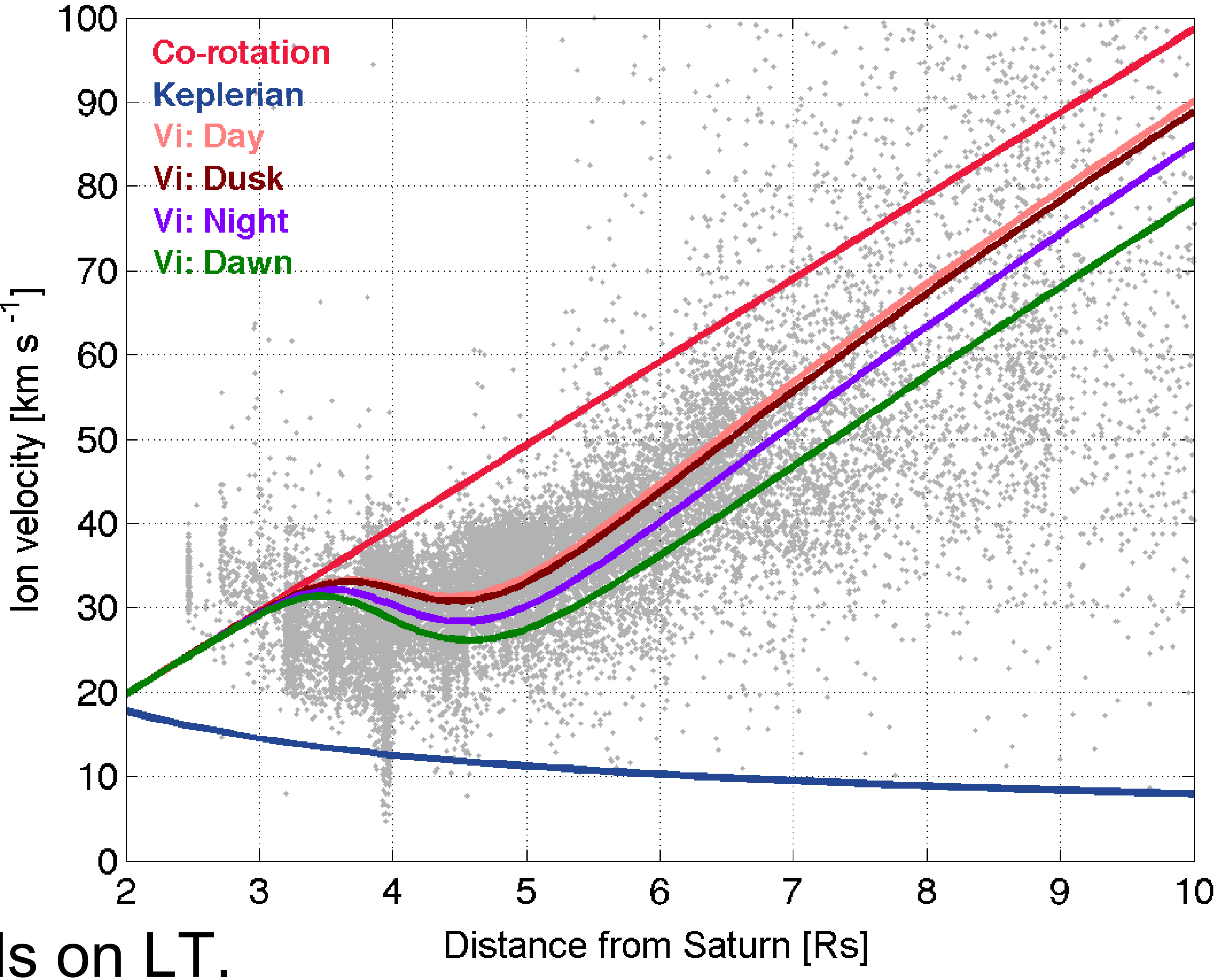


# Magnetospheric ion velocity

$$\boxed{\Sigma_i}\left(\mathbf{E}_{cor} - \mathbf{E}\right) = \mathbf{j}D$$



- $V_i$ depends on LT.

# Summary

- Ionospheric plasma distribution
  - $H_3^+$ is dominant at L=5.
    - Peak: $10^9$-$10^{10}$ $m^{-3}$
  - $T_e$ is much higher than that of previous studies at high altitude.
    - 2000 K at ~1200 km; 10000 K at ~5000 km
  - Joule heating and collision heating are important at low altitude, and heat flow at high altitude.
- Ionospheric conductivity
  - Pedersen conductivity depends on LT.
    - Day > Dusk > Night > Dawn
  - The magnetospheric ion speed shows the same tendency as the diurnal variation of conductivity.

# Conclusion

- Ion speed is slow down from the co-rotation speed due to **dust-plasma interaction** and **magnetosphere-ionosphere coupling**.
- The inner magnetosphere and ionosphere are **strongly coupled**.